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14. ABSTRACT
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A variety of scientific issues related to model initialization, forcing, open boundary conditions, and model spin up are discussed. The focus of this paper is on: the sensitivity of the horizontal resolution of atmospheric forcing on the NCOM-CCS model predictive skills; the impact of open boundary conditions and coupling with global models on reproducing major hydrographic conditions in the California Current System; and the analysis of the model mixed layer predictions and data assimilation issues. Qualitative and quantitative comparisons are made between observations and model predictions for October 2000 - December of 2001 period.

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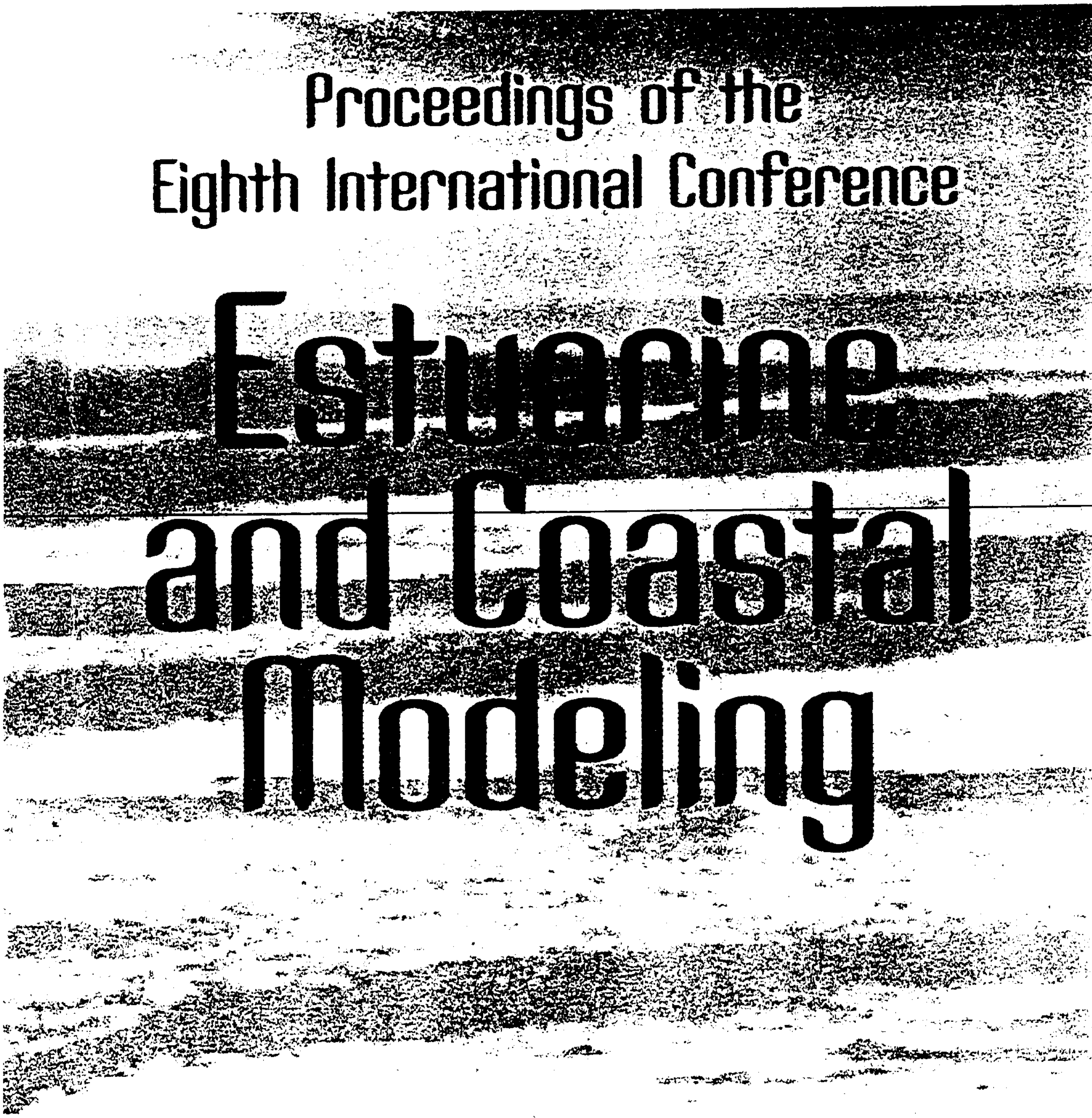

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Development of a hierarchy of nested models to study the California Current System.

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Abstract

The Naval Research Laboratory has developed a hierarchy of differing resolution data assimilating models in the Pacific Ocean, which includes global models, regional U.S. West Coast models, and high resolution coastal models such as for the Monterey Bay area. The three regional U. S. West Coast models (from 30°N to 49°N), designed to study the California Current System, are based on the Princeton Ocean Model (POM), the Navy Coastal Ocean Model (NCOM), called NCOM-CCS, and the Hybrid Coordinate Ocean Model (HYCOM), respectively. The NCOM-CCS formulation is a parallel version model capable of running reliably on many computer platforms. The model has nesting capabilities and offers the choice of using the sigma or a hybrid (sigma-z) vertical coordinate. The NCOM-CCS model also includes a coupled ecosystem model based on Chai et al., 2002.

A variety of scientific issues related to model initialization, forcing, open boundary conditions, and model spin up are discussed. The focus of this paper is on: the sensitivity of the horizontal resolution of atmospheric forcing on the NCOM-CCS model predictive skills; the impact of open boundary conditions and coupling with global models on reproducing major hydrographic conditions in the California Current System; and the analysis of the model mixed layer predictions and data assimilation issues. Qualitative and quantitative comparisons are made between observations and model predictions for October 2000 - December of 2001 period.

1. Introduction

To accommodate the wide range of horizontal scales of physical and biological oceanic processes, the Naval Research Laboratory (NRL) uses a nested modeling approach in which global models provide boundary data to regional scale models which, in turn, feed coastal models and so on (Figure1). Three large-scale models are shown in Figure 1: the global Navy Layered Ocean Model (NLOM, Wallcraft et al, 2002), the global model based on Navy Coastal Ocean Model (NCOM, Rhodes et al, 2002), and Pacific Ocean model based on Hybrid Coordinate Ocean Model (HYCOM, Bleck, 2002). The global NLOM is an isopycnal model with seven vertical levels (six active dynamical levels and mixed layer model) and horizontal grid resolution of 1/16° to better resolve fronts and eddies (Hurlburt et al, 1996). The NLOM assimilates satellite SSH and SST and is run as an operational model for the US Navy, some results of which may be viewed online (www7320.nrlssc.navy.mil/global_nlom). The NCOM based global model uses a hybrid vertical coordinate system (sigma levels up to 150m depth, z levels at the bottom) with 1/8° horizontal resolution and is run in real-time (www7320.nrlssc.navy.mil/global_ncom); the model is presently in the final stages of validation and evaluation for operational use (Rhodes et al, 2002). Global NCOM has been spun up from a climatological state to the present, using a combination of NOGAPS (Navy Operational Global Atmospheric Prediction System) forcing and the assimilation of 3-dimensional temperature and salinity observations derived from the Modular Ocean Data Assimilation System (MODAS; Fox et. al, 2002). The Pacific Ocean HYCOM (Hybrid Coordinate Ocean Model) has 1/12° horizontal resolution and 20 vertical levels; this research model is a proxy for the future development of a real-time global HYCOM with 1/12° resolution in 2006. HYCOM uses the hybrid vertical isopycnal-sigma-z level coordinate system (Bleck, 2002; Chassignet, 2003; oceanmodeling.rsmas.miami.edu/hycom).

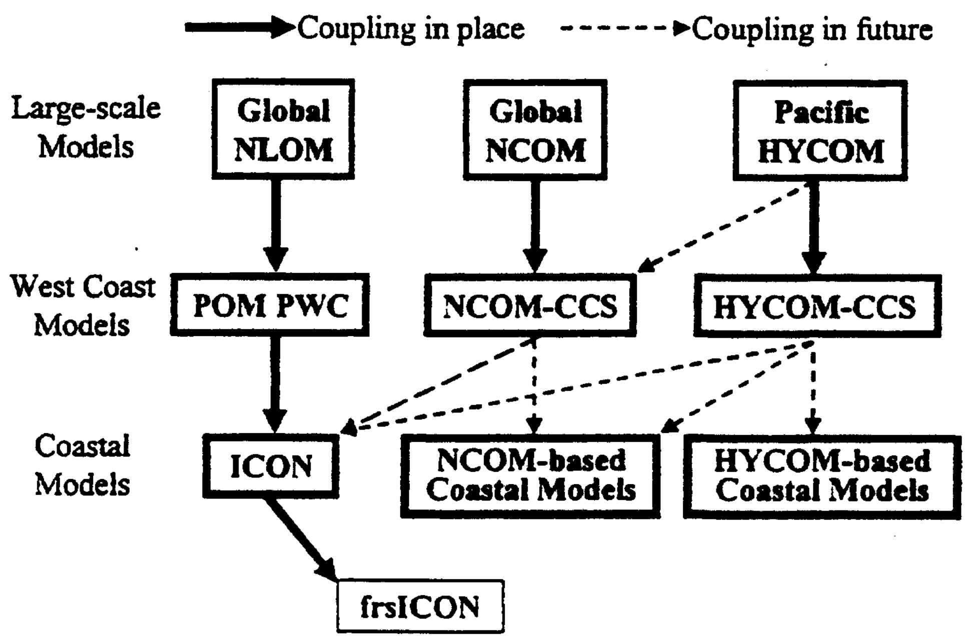

Figure 1. Diagram of the hierarchy of NRL models.

The second row in Fig. 1 presents three basin scale models of the US Pacific West Coast: POM-PWC (Haidvogel et al, 2000) is the model based on Princeton Ocean Model (Blumberg and Mellor, 1987), NCOM-CCS (California Current System) is the model based on the NCOM model (see below for more information), and the third is the HYCOM-based model (HYCOM-CCS). Both POM-PWC and NCOM-CCS have the same horizontal 9km resolution while HYCOM-CCS uses a grid resolution of ~7-8 km; all three models have the same domain which extends from 30°N to 49°N of latitude and from the coast to 135°W of longitude. POM-PWC and NCOM-CCS have 30 sigma vertical levels, and HYCOM-CCS has 20 vertical levels.

Figure 1 also presents two fine resolution models of the Monterey Bay. One of the models was initially developed under National Oceanic Partnership Program (NOPP) "Innovative Coastal-Ocean Observing Network" (ICON) project (Shulman et al, 2002). This model is based on the Princeton Ocean Model, and has a variable horizontal resolution ranging from 1-4 km and 30 vertical sigma levels. Another fine resolution Monterey Bay area model (frsICON) is nested inside of the ICON model, and has variable horizontal resolution ranging from 0.5 km to 1.5 km (this model was used for fine-resolution modeling of bioluminescence distributions in the Monterey Bay (Shulman et al., 2003)).

One of the objectives for the development of this hierarchy of different resolution models is the testing and evaluation of POM, NCOM and HYCOM based models in basin-scale and coastal environments. Another objective is determining the best combination of these nested models for the development of coupled bio-optical and physical models aimed at studying the California Current System. Additionally, the use of nested models permits one to use atmospheric forcing products that range from global to regional/local in scale. The impact of higher resolution atmospheric products is an important open question in ocean modeling. There are many different issues that arise from the development of these nested models (Fig. 1) such as those associated with coupling models with different physics, vertical coordinate systems and numerics, the sensitivity to the model's initialization and data assimilation schemes, and the sensitivity to the resolution of the atmospheric forcing. The goals of this paper are to briefly describe the nested system at NRL for the US west coast and to relate experiences in examining the impacts of our choices in the development of such nested models.

Given space limitations, the primary focus of the paper is on modeling issues using the NCOM-CCS formulation. In section 2, additional details of NCOM-CCS model are provided. Section 3 illustrates the sensitivity of the model predictions to the different resolution of atmospheric forcing. Coupling between NCOM-CCS and global NCOM are discussed in the Section 4, and some results from the California Current Ecosystem modeling are presented in Section 5. Finally, Section 6 discusses conclusions and future plans.

2. NCOM-CCS

The NCOM-CCS has a free surface and is based on the primitive equations and the hydrostatic, Boussinesq, and incompressible approximations (Martin, 2000; Rochford and Martin, 2001). The model uses an Arakawa C grid and is leapfrog in time with an Asselin filter to suppress time splitting. The propagation of surface waves and vertical diffusion are treated implicitly. A choice of the Mellor-Yamada Level 2 or Level 2.5 turbulence models is provided for the parameterization of vertical mixing. The horizontal resolution of the model is around 9km, and the model has 30 vertical sigma levels. The model assimilates ~14 km daily Multi-Channel Sea Surface Temperature (MCSST). The model is one-way coupled to the 1/8° global NCOM (details of coupling scheme are presented in section 4).

The NCOM-CCS also includes a 9-component ecosystem model; the biological model was implemented into the NCOM in collaboration with Dr. Fei Chai (Chai et al, 2002). The biological model, a 9-component ecosystem formulation originally developed for the equatorial Pacific upwelling system, includes three nutrients (silicate, nitrate and ammonia), two phytoplankton groups, two zooplankton grazers, and two detritus pools.

3. Sensitivity of NCOM-CCS model predictions to the resolution of atmospheric forcing.

A variety of atmospheric products were used to assess the sensitivity of the NCOM-CCS model to the resolution of the wind forcing. Wind products derived from the European Center for Medium Range Forecasting (ECMWF; 1.125° resolution), NOGAPS (1° resolution atmospheric model) and the Navy's Coupled Ocean Atmosphere Mesoscale Prediction System (COAMPS™; Hodur, 2002) atmospheric models were used in sensitivity studies with NCOM-CCS. For the COAMPS™ product, winds from the COAMPS™ Reanalysis for the Eastern Pacific (EP) were used (Kindle et al, 2002); these atmospheric winds exist on a triply nested 81/27/9 km grid beginning in November of 1998. The COAMPS™ EP Reanalysis fields on the native Lambert Conformal grid were interpolated to the latitude-longitude coordinate ocean model grid with ~ 9km resolution. A weighted-average bilinear interpolator (WABI) with ocean/land-discrimination was developed and used to interpolate (project) atmospheric forcings from 9/21/81 grids of the COAMPS™ to the grid of the NCOM CCS.

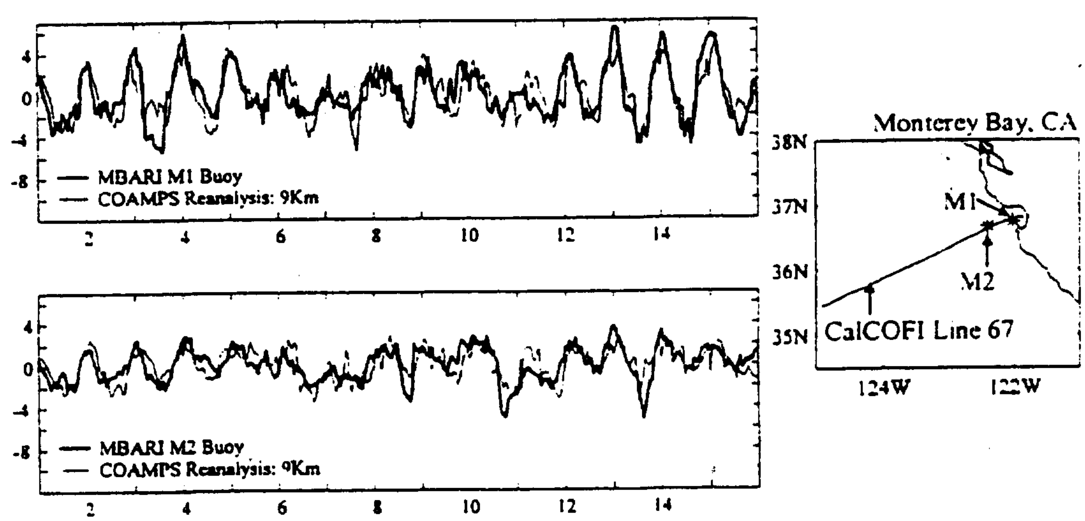

Figure 2. Observed and model-predicted wind velocities (projected on principal axis) at moorings M1 and M2.

Figure 2 demonstrates the quality of winds from COAMPS™ 9km predictions. Filtered observed and model predicted wind velocities (projected on principal axis) are shown at two mooring locations (M1 and M2) in the Monterey Bay area. COAMPS™ model reproduced nicely observed diurnal variability, and observed shoreward intensification of the diurnal amplitude (see also, Kindle et al., 2002).

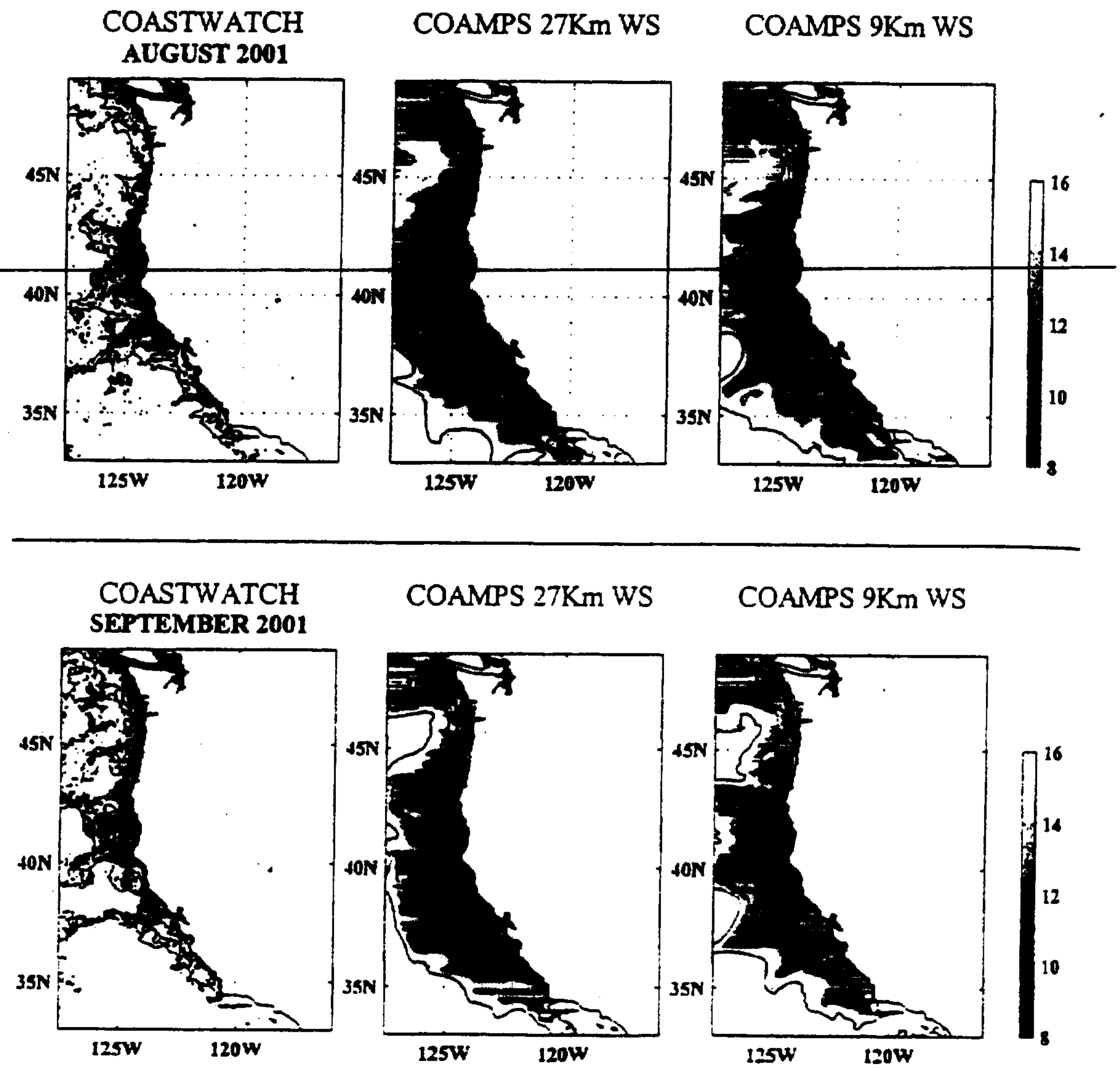

Figure 3. Comparisons between monthly mean NCOMCCS model SST and CoastWatch SST monthly composites.

Figure 3 shows comparisons of mean model-predicted and observed SST for August and September of 2001. One can see that model forced with 27km and 9km COAMPS™ winds nicely reproduce the meandering front between the warmer water of California Current and the upwelled water along the coast. At the same time, this front and observed features have a sharper representation in model simulations with finer 9km resolution wind. Quantitatively, the sensitivity of the NCOM-CCS model predictions to different resolution wind forcing was studied with a comparison of model predicted and observed velocities at mooring M1 (location of which is shown on Fig. 2). It should be noted that it is a very challenging task for any resolution physical model without data assimilation to show a good predictive skill of the velocity field along the central California coast, particularly near the Monterey Bay region. Mooring M1 is located in the transition zone between the California Current and upwelled water, and the front between these water masses--sometimes in the shape of the anticyclonic eddy-- migrates onshore-offshore depending on relaxation or upwelling favorable wind conditions.

The magnitudes of complex correlation coefficients and angular displacements between the observed and model-predicted currents were used for comparisons. The magnitude ρ of the complex correlation coefficient between the ADCP and NCOM-CCS model currents and the angular displacement θ (phase angle, average veering) for a particular depth were estimated by using the approach outlined in Kundu (1976). The magnitude of ρ is estimated using the following formula: $\rho = \sqrt{Re^2 + Im^2}$, where

$$Re = \frac{\sum_t \left(u_t^o u_t^m + v_t^o v_t^m\right)}{\sqrt{\sum_t \left(\left(u_t^o\right)^2 + \left(v_t^o\right)^2\right) \sum_t \left(\left(u_t^m\right)^2 + \left(v_t^m\right)^2\right)}}, \text{ and}$$

$$Im = \frac{\sum_t \left(u_t^o v_t^m + v_t^o u_t^m\right)}{\sqrt{\sum_t \left(\left(u_t^o\right)^2 + \left(v_t^o\right)^2\right) \sum_t \left(\left(u_t^m\right)^2 + \left(v_t^m\right)^2\right)}}.$$

The corresponding angular displacement θ (phase angle, average veering) for particular depth is estimated according to:

$$\theta = \tan^{-1} \frac{\sum_t \left(u_t^o v_t^m - v_t^o u_t^m\right)}{\sum_t \left(u_t^o u_t^m + v_t^o v_t^m\right)},$$

where, u_t^m, v_t^m and u_t^o, v_t^o are demeaned model and observed east-west and north-south components of velocity. The angular displacement θ gives the average counterclockwise angle of the NCOM-CCS currents with respect to the ADCP currents. The value of θ is only meaningful if ρ is significant. Standard statistical techniques (see, for example, Emery and Thomson, 1998) were used for estimating 95% significance levels of the correlation. For the period of 15 June – 15 September of 2001, the significant level is 0.144. Figure 4 shows the magnitude of complex correlation and angular displacements between observed and model predicted currents up to 120m depth. In Figure 4a, the comparisons are shown for model runs when direct (atmospheric model predicted) wind stresses were used. On the bottom (Figure 4b), wind stresses were estimated from 10m wind velocity by using the Large and Pond (1981) formulation. Comparisons are shown for three model runs forced with COAMPS™ (81km/27km/9km) resolution winds, respectively. The magnitude of the correlation between model-predicted and observed currents increases as wind resolution increases. Also, the average angle between model and observations is improved with increase in wind resolution. Use of Large and Pond derived stresses degraded the predictions with coarser resolution winds (81 and 27km). However, it improved model predictions at the surface when the model is forced with 9km wind. Overall, though, the model shows low correlation with observed currents. In previous research (Shulman et al, 2001, Paduan and Shulman, 2003) it was demonstrated that assimilation of HF radar-derived surface currents improves the coastal Monterey Bay (ICON) model currents predictions. Hence, it is expected that the assimilation of HF radar-derived surface currents from installations along the coast will improve the NCOM-CCS currents predictions, as well. HF radar-derived surface currents assimilation into the regional scale NCOM-CCS model is a topic for future research.

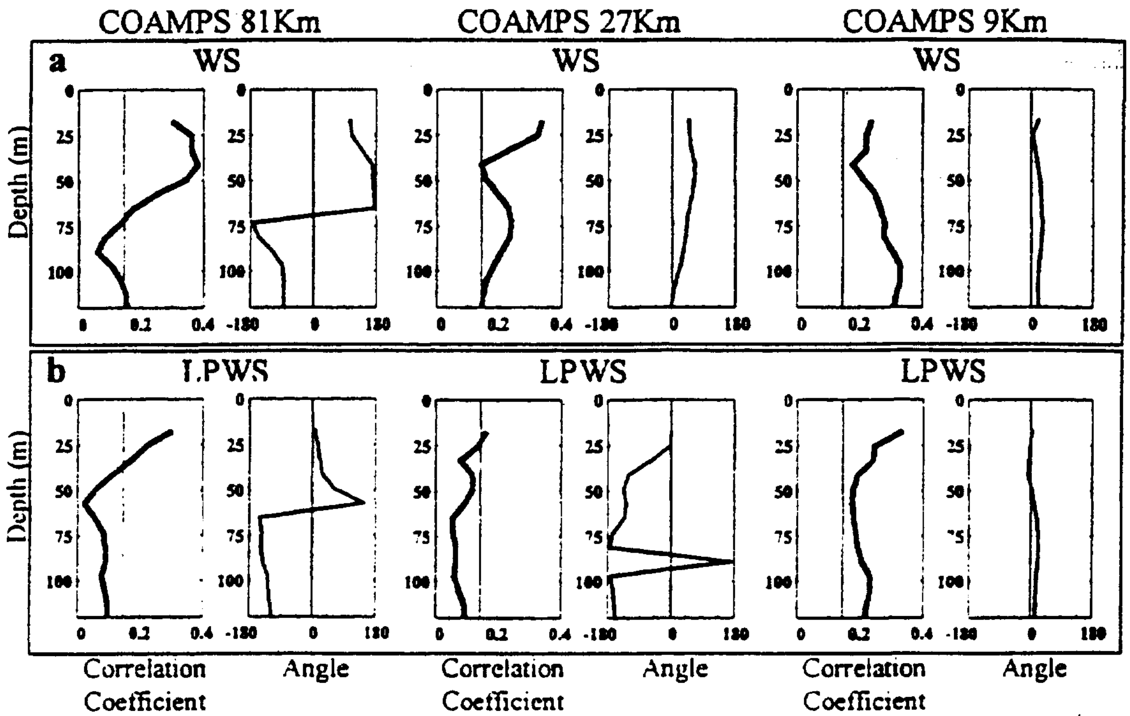

Figure 4. Magnitude of complex correlation and angular displacements between observed and model predicted currents for three model runs with different resolution wind forcing. a - Direct Stresses (WS), b - Large & Pond Stresses (LPWS)

4. Coupling NCOM-CCS with NCOM based global model.

Table 1 presents boundary conditions which are used for one way coupling between NCOM-CCS and global NCOM. Sea surface elevations and vertically averaged velocities (barotropic information) from the global NCOM and NCOM-CCS are coupled through the Flather (1976) boundary condition for the NCOM-CCS model (this open boundary condition represents a radiation condition on differences between NCOM-CCS and global model sea level elevations and transports). The baroclinic coupling consists of using the vertical structure of velocity, temperature, and salinity from the global model in specification of the vertical distributions of NCOM-CCS fields (see Table 1).

The coupling between NCOM-CCS and the global model was evaluated by comparing model-predicted and observed sea level elevations at tidal stations along the coast. Figure 5a shows comparisons at the San Diego station which is the closest station to the southern open boundary of the NCOM-CCS model domain. On Figure 5a, a 3-day moving average of observed and model-predicted sea level elevations are shown when barotropic, as well as baroclinic couplings were used according to Table 1. The model demonstrated a reasonably good skill in prediction of sea level elevation; the correlation is around 0.82, and skill score (estimated according to Murphy and Epstein, 1989) is around 0.62. Also, on Figure 5a, the comparisons are shown for the model run, when the radiation condition was used for normal baroclinic velocity instead of the advectional open boundary condition (Table 1).

Table 1. Coupling NCOMCCS with NCOM global.

Variables	Open Boundary condition
Elevation and normal barotropic velocity	Flather radiation condition. Radiation condition for differences between NCOMCCS and NCOM global elevations and normal barotropic velocities.
Normal baroclinic velocity	Advectional boundary condition Overflow case – velocity from first interior grid is advected to the NCOMCCS open boundary. Inflow case – NCOM global velocity is advected to the NCOMCCS open boundary
Tangential barotropic and baroclinic velocity	Zero Gradient condition NCOMCCS tangential velocity is set equal to the values at the first interior grid next to the open boundary.
Tracers (T, S and biology constituents)	Advectional boundary condition Outflow case – values from first interior grid are advected to the NCOMCCS open boundary Inflow case – NCOM global values (T and S) and derived from external source biology data are advected to the NCOM-CCS open boundary

In this case, no external baroclinic information about structure of the baroclinic velocity was used in specification of open boundary conditions for the baroclinic velocity of the NCOM-CCS. It is evident that the model predictive skill at San Diego station was significantly degraded without the use of baroclinic velocity from the global NCOM model. At the same time, the importance of baroclinic coupling diminishes as one moves from the southern to the northern boundary of the domain. In Figs 5b and 5c, comparisons are shown for stations at Crescent City (which is somewhat in the middle of the model domain) and for Neah Bay station, which is closest to the northern open boundary of the model domain.

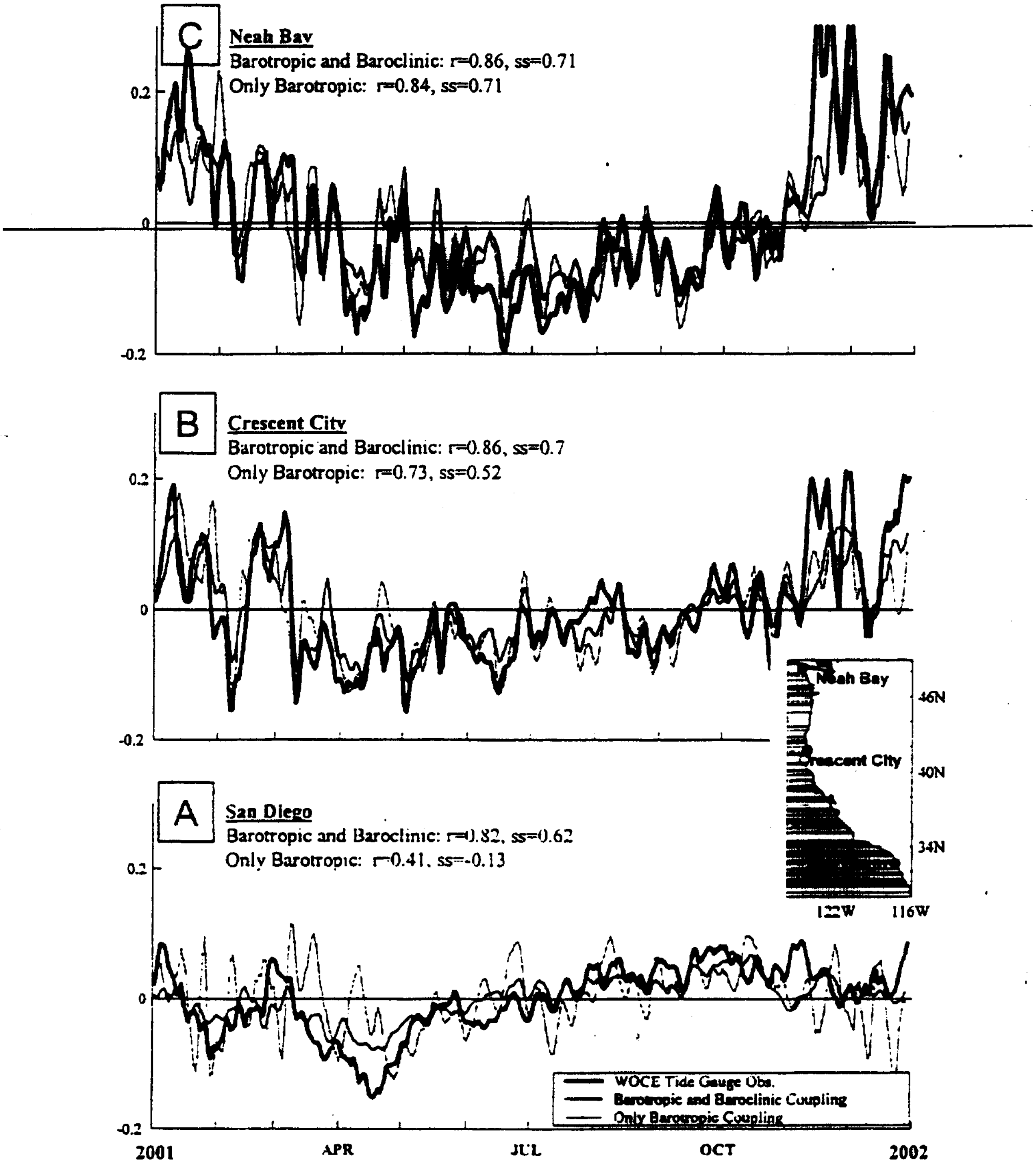

Figure 5. Sea surface height anomaly comparison with WOCE tide gauge stations. Data shown are 3-day average of daily data.

At the Neah Bay station (Fig. 5c), the model skills for runs with and without baroclinic coupling are very similar. This can be explained by the fact that remote baroclinic signal (supplied by global model to NCOM-CCS) propagates from south to north and diminishes along the coastal area of the model domain.

Fig. 6a shows comparisons of observed and model-predicted mixed layer depths (MLD) at the mooring M1. MLD was defined as depth at which the water temperature becomes 0.1°C less than SST (Martin, 1985). The plotted observed MLD (Figure 6a) has very low variability during summer time because of poor vertical resolution of available observations in upper 20 meters. The model reproduces the shallowing of mixed layer during the summer time, and deepening of MLD during transition to the winter time. However, without the baroclinic coupling, the model misses some observed events of shallowing MLD during summer time and deepening during the transition to the winter.

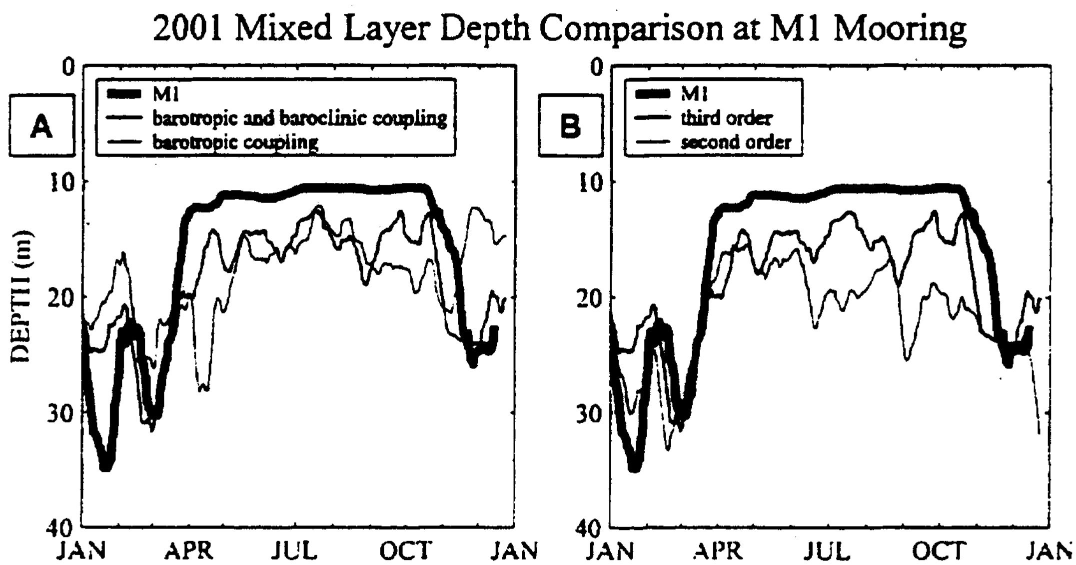

Figure 6. Observed and model-predicted mixed layer depth (MLD) comparison at the M1 Mooring.

Comparisons of MLD for two model runs, in which third and second order advection schemes were used, are displayed in Figure 6b. The MLD for the run with second order advection has significantly less variability during summer and during the transition to the winter. This supports the well-known fact that frontal structures are more diffused by second order advective schemes than third order schemes. Overall, despite the MCSST assimilation into the NCOM-CCS model, model-predicted MLD is deeper than the observed. The assimilation of MCSST does not adequately compensate for the over-mixing in the model. This points to the necessity of including of heat fluxes, especially evaporative heat flux, into the NCOM-CCS surface boundary conditions to produce thinner mixed layers during the summertime.

5. Modeling of California Current Ecosystem with NCOM-CCS.

The NCOM-CCS model also includes coupling to the 9-component ecosystem model implemented in collaboration with Dr. Fei Chai (Chai et al, 2002). The biological model, a 9-component ecosystem formulation originally developed for the equatorial Pacific upwelling system, includes three nutrients (silicate, nitrate and ammonia), two phytoplankton groups, two zooplankton grazers, and two detritus pools. Figure 7 shows a comparison of model-predicted and SeaWIFS ocean color satellite derived chlorophyll fields for July, 2001. The model is able to represent the horizontal scale of the phytoplankton bloom due to summertime upwelling favorable winds. The model is also able to reproduce the approximate magnitude and offshore extension of the coastal blooms near Cape Blanco (~ 42.5°N) and Heceta Bank (~ 44.5°N).

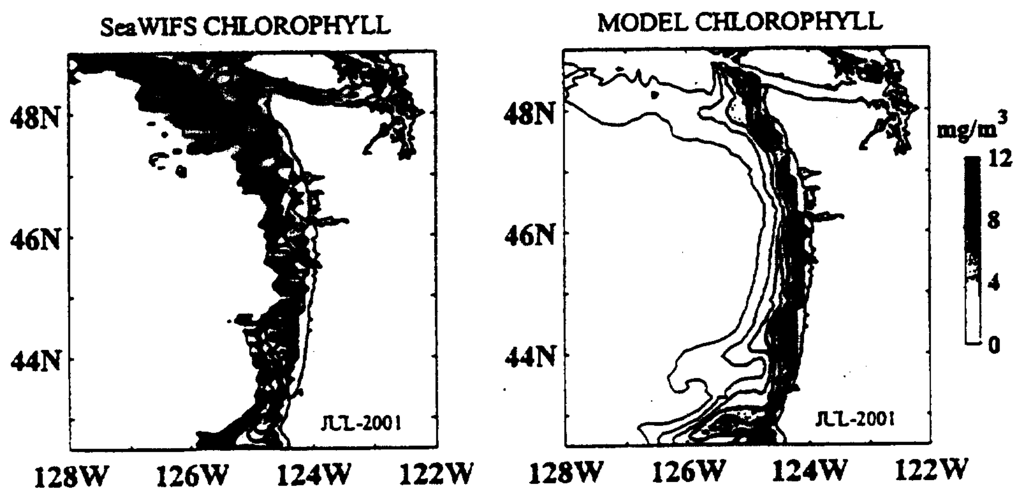

Figure 7. Surface chlorophyll comparison of observed SeaWifs (July 2001) composite and mean monthly chlorophyll from NCOMCCS model embedded with a 9-compartment biological model.

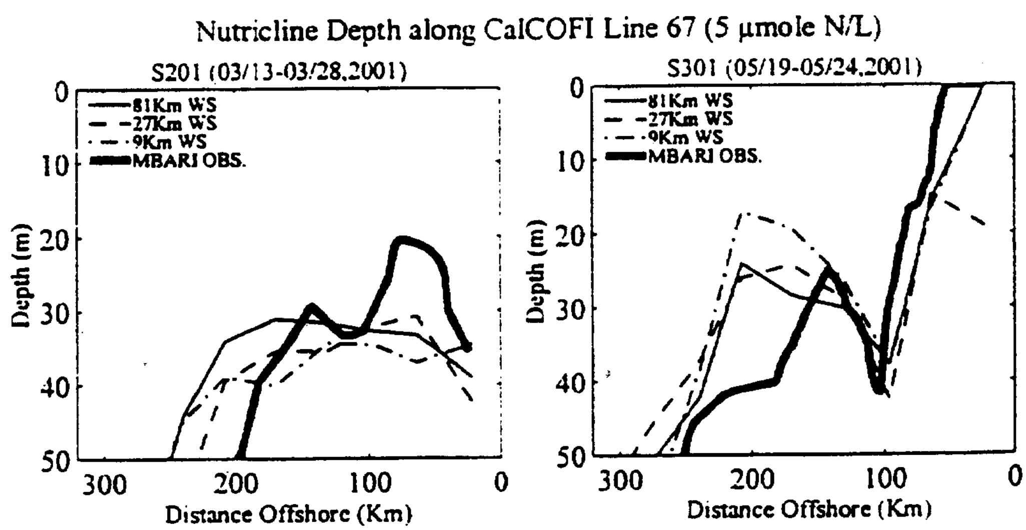

Figure 8. Comparison of observed and model predicted nutricline depths along CalCOFI Line 67. Three model runs forced with different resolution wind stresses are shown.

Figure 8 demonstrates comparisons of model predicted and observed nutricline depths. The nutricline depth is defined as the depth where the concentration exceeds 5 μmol N m^{-3}. Comparisons are shown along California Cooperative Oceanic Fisheries Investigations (CalCOFI) line 67 (see map on figure 2) for CalCOFI surveys in March and May of 2001. Without any assimilation of biological observations we should not expect one to one correspondence between model and observations. However, the model is able to reproduce the observed variability and depth of the nutricline well. There are three model runs forced with different resolution wind stresses are shown on Fig. 8. All three runs show similar results and therefore weak dependence of the nutricline depth on resolution of the wind forcing.

6. Discussions and future plans

The NCOM-CCS model simulations demonstrated a good predictive skill in reproducing features and observed variability in SST and SSH fields. The correlation between the model-predicted and observed ADCP currents is higher than the 95% significance level when the model is forced with COAMPS™ 9km resolution wind. The model reproduces the seasonal variations in mixed layer depth: shallowing of mixed layer during the summer time, and deepening of MLD during transition to the winter time. The NCOM-CCS model predictions demonstrated the importance of the baroclinic coupling with the NCOM global model for accurate predictions of SSH variability along the US West Coast (especially, in prediction of SSH at southern portion of the model domain). NCOM model has flexible options for choosing different order advective schemes. Seasonal variability of the model-predicted depth of the mixed layer agreed better with observations when the third order advective scheme was used. The NCOM-CCS model also includes coupling to the 9-component ecosystem model implemented in collaboration with Dr. Fei Chai (Chai et al, 2002). The model was able to represent the horizontal scale of the phytoplankton bloom due to summertime upwelling favorable winds, and the model was able to reproduce the observed variability of the nutricline depth.

At the same time, comparisons between observations and model results show that even with high resolution atmospheric forcing, the model shows low correlation with observed currents. The model predicted mixed layer depth is deeper than what was observed during the summer time. The above and other discrepancies between model predictions and observations suggest future research items aimed at improvement of the NCOM-CCS model predictions:

- Inclusion of heat fluxes and air-sea coupling with COAMPS™ predictions
  Coupling with atmospheric model is needed for the improvement of model predictions of mixed layer depth, especially during the summer time.
- Assimilation of MODAS synthetic temperature and salinity profiles.
  The global model (which assimilates MODAS fields) provides boundary conditions for NCOM CCS. Without assimilation of MODAS fields into the NCOM CCS, the model dynamics inside of

the model domain might drift significantly from open boundary values, which will lead to the development of artificial waves along the open boundaries. This is why assimilation of MODAS fields in NCOM CCS is probably needed for long duration runs.

- Assimilation HF radar derived surface currents from installation along the US West Coast.

  This is needed for the improvement of model-predicted currents close to the coast and for a better correlation with observations.

- Doubling of horizontal resolution up to 4.5 km.

  Transition of the NCOM CCS model to 4 -4.5 km of horizontal resolution will be a significant improvement in physical as well as ecosystem modeling.

- Assimilation of bio-optical observations.

  With a high level of uncertainty in values of the ecosystem model parameters and ecosystem modeling, assimilation of observations, for example, ocean color measurements is needed.

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